COSMIC RAYS IN THE 10^{16} TO 10^{19} eV RANGE FROM PULSARS

Amri Wandel and Donald C. Ellison

Astronomy Program, University of Maryland, College Park, Maryland 20742

Abstract. We calculate the flux of cosmic rays (CRs) produced by a distribution of pulsars that are (1) born with rapid rotation rates, (2) slowdown as they evolve, and (3) produce energetic nuclei with a characteristic energy proportional to their rotation rates. We find that, for energy independent escape from the disk of the galaxy, the predicted spectrum will be essentially what is observed between ~ 10^{16} to 10^{19} eV if the slowdown law as inferred for radio pulsars can be extrapolated to young pulsars with shorter periods.

1. Introduction. The recent discovery of ultra-high energy γ-rays from compact sources such as Cygnus X-3 (Samorski and Stamm 1983) has renewed speculation that compact objects may produce a significant fraction of the observed galactic CRs (Hillas 1984b; Chanmugam and Brecher 1985). Almost immediately upon the discovery of pulsars, they were suggested as possible sources of CRs (e.g. Ostriker and Gunn 1969). However, two major problems led most researchers to discount pulsars as important contributors to the CR flux. The first is the highly unlikely possibility that pulsars can produce nuclei in the GeV range with the observed CR composition. The observed composition at these energies is essentially the same as universal abundances (e.g. Meyer 1985) and strongly argues against sources as exotic as pulsars.

The second problem concerns the ability of pulsars to produce ultra-high energy nuclei. Pulsars store vast amounts of energy in their rotational motion, and their large surface magnetic fields combined with rapid rotation imply vacuum potentials in the CR energy range. However, it was considered doubtful that pulsars could produce nuclei with energies even remotely approaching the limit of their vacuum potentials (e.g. Arons 1981).

Recent developments have prompted us to reexamine pulsars as possible CR sources. First, a relatively self-consistent explanation for CRs below ~ 10^{15} eV has been developed (e.g. Axford 1981). In this model, expanding supernova blast waves accelerate CRs out of the ambient interstellar medium. While many important details remain to be clarified, supernovae, combined with first-order Fermi shock acceleration, can be expected to account for the observed CR energy spectrum, energy budget, and composition up to ~ 10^{15} eV. Above this energy, however, it becomes highly unlikely that supernova shocks can accelerate particles (Lagage and Cesarsky 1983; Wandel 1985; for an alternative view, see Jokipii and Morfill 1985). A feature in the CR spectrum is seen near 10^{15} eV and the spectrum steepens above ~ 10^{16} eV, suggesting that these CRs may have a distinct origin. From ~ 10^{16} to 10^{19} eV the observed CR spectrum is well described by a power law with index -3 (e.g. Hillas 1984a). Measurments of the composition become very difficult at these energies and few constraints on CR composition exist above ~ 10^{16} eV.

Second, Michel and Dessler (1981) have proposed that active radio pulsars may be surrounded by fossil disks left over from the collapse that produced the neutron star. In this model, the neutron star and disk act essentially as two coupled unipolar generators and are capable of maintaining potential differences of the order of the vacuum potential, i.e., $\sim a^2 B\Omega$, where a is the radius, Ω is the angular velocity, and B is the surface magnetic field of the pulsar. These authors suggest that nuclei can be accelerated from the disk (having near solar abundance) to energies on the order of this potential.

We also note that γ-rays with energies in excess of 10^{16} eV have been observed from Cgynus X-3 (Samorski and Stamm 1983). This is reasonably clear proof that compact objects can accelerate nuclei to CR energies regardless of our inability to understand how they do it.

In light of this, we examine a simple model for the production of CRs by a galactic distribution of pulsars. These pulsars would be born with high magnetic fields and millisecond (ms) periods, and would evolve according to the slowdown relation, $d\Omega/dt \propto \Omega^n$, where n is the braking parameter. The range in radio pulsar periods implies that this source would cutoff below $\sim 10^{16}$ eV and produce CRs rays up to $\sim 10^{19}$ eV, where another feature in the spectrum is observed. Cosmic rays above $\sim 10^{19}$ eV would be produced by yet another source that is most likely extragalactic (Hilles 1984a).

2. Model. We assume that pulsars are born at the rate, $Q(\Omega)$. Their evolution may be described by a diffusion equation in Ω space:

$$\frac{d}{d\Omega}(N\,\dot{\Omega}) = Q(\Omega), \tag{1}$$

where $\dot{\Omega} = d\Omega/dt$ and $N(\Omega)d\Omega$ is the number of pulsars per unit volume in $d\Omega$. For simplicity we assume that all pulsars are born with the same Ω_{max}, i.e., $Q(\Omega) = Q_o\,\delta(\Omega-\Omega_{max})$. Equation (1) can then be solved to give

$$N = -\,Q_o/\dot{\Omega}. \tag{2}$$

Now, on very general terms, the magnetic torque should slow the pulsar so that

$$\dot{\Omega} \propto \Omega^n, \quad \text{with } n = 3. \tag{3}$$

This result, which is essentially a dimensional consideration and is quite model independent, is also backed by observations of radio pulsars (for a detailed discussion see Michel 1982).

Next we assume that pulsars produce nuclei with energies comparable to the vacuum potential, i.e.,

$$E_{vp} \sim \frac{e}{c}\,a^2 B\Omega \sim 6 \times 10^{19}\left(\frac{a}{10\text{ km}}\right)^2\left(\frac{10^{-3}\text{s}}{P}\right)\left(\frac{B}{10^{12}\text{ G}}\right)\text{eV}, \tag{4}$$

where P is the pulsar period in seconds.

The particle spectrum produced by a distribution of pulsars, each having a differential flux, $f_\Omega(E)$, is given by

$$F(E) = \int N(\Omega) f_\Omega(E)\,d\Omega. \tag{5}$$

If the particle spectrum of a specific pulsar is peaked at its vacuum potential, i.e., $f_\Omega(E) \propto \delta[E-E_{vp}(\Omega)]$, eqs. (2)-(5) can be solved to yield

$$F(E) \propto E^{-n}, \quad 10^{16} \lesssim E \lesssim 6 \times 10^{19}\text{ eV}, \tag{6}$$

where we have assumed that the flux of particles emitted by a pulsar is independent of Ω. The energy range is determined by a spread in pulsar periods from ~ 1 ms to 4 s. If n = 3, this is just the observed slope of the CR spectrum in the above energy range.

The above solution can be shown to be independent of the spectrum emitted by an individual pulsar. For an emitted spectrum of the form

$$f_{\Omega}(E) \propto \Omega^{q} E^{\alpha}, \tag{7}$$

we find that $F(E) \propto E^{-n+q}$ and is essentially independent of α if $\alpha > -1$ (Wandel and Ellison 1985).

3. Discussion It is remarkable that a straightforward application of zeroth-order pulsar theory yields a spectrum consistent with the observed CR spectrum above ~ 10^{16} eV. There are, however, many complicating factors that may alter this result. (a) Pulsars may be born with a distribution of periods, or with periods considerably longer than 1 ms. We note that the ms pulsars that have been observed to date may have been spun-up, have low magnetic fields, and would not produce the energetic particles we envision. A recent survey at 1.4 GHz (Manchester et al. 1985) suggests, however, that many short-period pulsars would be discovered by searches with improved sensitivity. (b) Pulsars may not produce nuclei at energies near the vacuum potential. Cygnus X-3 produces highly energetic nuclei, but is not of the class of objects considered here. (c) Instead of a delta function at E_{vp} as we have assumed, an individual pulsar may produce particles with a distribution of energies. However, due to the rapid pulsar evolution, the distribution of CRs produced by a population of pulsars is insensitive to the shape of the spectrum from a single pulsar, as discussed above. (d) We assume that the particle flux produced by an individual pulsar is independent of Ω [i.e. $|q| \ll 1$ in eq. (7)]. The flux is determined by the details of the pulsar model and may depend on the geometry and magnetic field, which are assumed to vary slowly. Note, however, that if the emitted particle flux is related to the rotational energy loss, $dE/dt = I\Omega\dot{\Omega}$ (I = moment of inertia), the flux would be expected to be a strong function of Ω. (e) The braking parameter may not be constant and equal to 3. For instance, if the neutron star has a finite quadrupole moment (e.g. due to an internal field or a secular rotational instability), gravitational radiation would be emitted. If the neutron star looses angular momentum mainly due to gravitational radiation, then n ~ 5. For parameters typical of the Crab pulsar (Ostriker and Gunn 1969; Alper and Pines 1985), gravitational quadrupole radiation dominates magnetic dipole radiation only for P < 1-2 ms, so that the relevant Ω range is not affected significantly. (f) We must consider the effect of propagation on the source spectrum, eq. (6). This is treated below.

At energies below ~ 10^{15} eV, the interpretation of the secondary to primary nuclei ratios implies that the CR source spectrum is significantly steepened by propagation and energy dependent escape from the galaxy (e.g. Protheroe et al. 1981). At the energies considered here, however, there is no direct evidence that the source spectrum is modified by propagation. On the contrary, if we extrapolate the inferred scattering mean free path, λ_s, from lower energies (Ormes 1983) to 10^{16} eV, we find it is (for protons) of the order of the scale height of the galactic disk, and increases for higher energies. This suggests that the diffusion approximation is not justified at energies above 10^{16} eV. If these high energy particles are not confined, the observed CR spectrum is not modified by an energy-dependent leakage term, as it is at lower energies, hence the slope of the observed spectrum will be the same as the source spectrum.

The observed CR flux above $\sim 10^{16}$ eV requires $\sim 4 \times 10^{50}/t_r$ erg/s, where t_r is the CR residence time in the disk and we have assumed a typical disk volume (e.g. Hillas 1984b). For scatter free propagation, $t_r \sim 10^{3.5}$ yr. However, the mean free path at $\sim 10^{16}$ eV may be smaller than the scale height of the disk (e.g. if heavy nuclei contribute), in which case t_r would be significantly larger (e.g. if $\lambda_s \sim 50$ pc, $t_r \sim 10^5$ yr). The energy required to power the observed CR spectrum above $\sim 10^{16}$ eV would, in that case, be $\sim 10^{38}$ erg/s (cf. Hillas 1984b). This is only a fraction of the rotational energy loss of the Crab pulsar ($I\Omega\dot{\Omega} \sim 5 \times 10^{38}$ erg/s). At higher energies, the residence time in the disk decreases to the scatter free value, but on the other hand, the energy required to power CRs decreases as 1/E while the energy input available from pulsars is $\propto NI\Omega\dot{\Omega} \propto E$. The rotational energy in pulsars is, therefore, more than sufficient to power CRs above 10^{16} eV.

In addition, the increase in anisotropy of CRs which is observed above $\sim 10^{15}$ eV, may also be due to the mean free path becoming comparable to the thickness of the disk. If λ_s is ~100 times the gyroradius, the transition energy should be in the range of 10^{15} to 10^{16} eV as observed.

4. Conclusions. We have found that the observed cosmic ray spectrum in the energy range, $\sim 10^{16}$ to 10^{19} eV can be produced by a distribution of pulsars if they are born with ms periods, evolve according to $\dot{\Omega} \propto \Omega^3$, and emit nuclei with energies characteristic of their vacuum potentials. As indicated, this simple model makes several assumptions, some of which are ad hoc. However, we find it remarkable that the proper CR spectrum and energy range are reproduced with minimal assumptions and with virtually with no free parameters. This result is essentially independent of the spectral details of individual pulsars.

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